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A SUMMARY OF UNDERWATER ACOUSTIC DATA

PART III
RECOGNITION DIFFERENTIAL

by

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PREFACE

This report is the third of a series which attempts to summarize existing knowledge about the parameters which appear in the sonar equations. These relationships, which find application in many problems involving underwater sound, are stated for reference in Part I of this series. As outlined in Part I, the objective of the summary is to provide a condensation of some of the basic data in underwater sound for use by practical sonar scientists. The present report deals with the detection of underwater sound signals in terms of the parameter, recognition differential. Material which could not be included in these Confidential reports will appear in a Secret Supplement to the series.

The recognition differential of a receiving system depends on a large number of variables which may or may not be independent. Only limited quantitative data on the subject is available, and it has been necessary to include in this summary considerable information of a descriptive nature, which, it is hoped, will assist the sonar scientist in arriving at a recognition differential for a given receiving system.

The complete series of reports is listed below:

Part I - Introduction (July 1953)

Part II - Target Strength (December 1953)

Part III - Recognition Differential (December 1953)

Part IV - Reverberation

Part V - Background Noise

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Manuscript submitted October 21, 1953

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INTRODUCTION

Definition of Recognition Differential

Every sonar system, whatever its ultimate purpose, represents the efforts of its designer to decrease the apparent background of noise or reverberation, and to increase the wanted signal. Indeed, one might say that most of the efforts of the designer, and much of the electronic complexity of the system, are aimed at improving the system's ability to discriminate against the background in favor of the signal. Many, and sometimes extreme, means are employed to provide this discrimination without impairing other desirable characteristics such as search rate in a detection system, or equipment simplicity and reliability.

As pointed out in Part I of this series, underwater sound is now utilized by the Navy for a considerable number of purposes. In addition to its historically initial function of detection of underwater objects, it is now employed for communication, target classification, torpedo homing, and in other ways.

In order to achieve its purpose, whatever it may be, an acoustic system requires a certain level of wanted signal relative to the background in which the signal appears. This needed signal-to-background ratio depends on the purpose being served; a sonar set requires one signal-to-background ratio for <u>detection</u>, a higher one for <u>target bearing</u>, and perhaps a still higher one for <u>classification</u>. The signal-to-background ratio required for <u>detection</u> of a target 50% of the time in a large number of independent trials is termed the <u>recognition differential</u>. It is defined to be the ratio, expressed in db, of the root-mean-square signal level to that of the background, measured at the output terminals of the transducer, when a signal is detected in 50% of a large number of independent trials. Broadband signals and noise backgrounds are specified in terms of their spectrum level, or their level in a 1-cps band; reverberation backgrounds are more conveniently specified in terms of total reverberation level, rather than spectrum level.

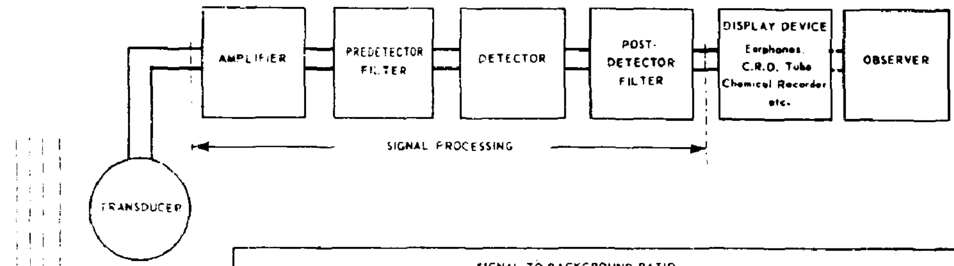
It is interesting to observe that, from the way recognition differential is defined, a <u>high</u> recognition differential means that a high signal-to-background ratio is required for detection and implies <u>poor</u> detection; similarly, a <u>low</u> recognition differential means <u>good</u> detection.

The fraction of trials in which a signal is detected is called the <u>detection probability</u>, and is arbitrarily taken to be 50% in defining recognition differential. While this is a satisfactory criterion of detectability for many purposes, in some problems a higher detection probability is more useful. The correction to the recognition differential which is required when a detection probability of other than 50% is more appropriate to the problem at hand is given by a transition curve, to be discussed later on.

Because of the fact that in practice both the signal and background fluctuate with time, recognition differential is defined in terms of the rms levels of signal and background averaged over a sufficiently long period of time. Some of the fluctuation is inherent in the source of

sound and in the transmission loss along the acoustic paths between the source and the receiving transducer. Even in laboratory experiments, inherent fluctuations remain in broadband signals and backgrounds. These fluctuations in the background are extremely important in masking small signals, and have a great effect in determining recognition differentials.

Figure 1 illustrates how the various parts of a sonar system contribute to the enhancement of the signal against background. The receiving transducer itself provides a portion of the enhancement of signal-to-background ratio through its directional properties, and the amount of its enhancement is given by its directivity index. The remainder of the improvement, provided by the signal processing method, the presentation employed, and the observer, is specified by the recognition differential.



SIGNAL-TO-BACKGROUND RATIO	
In water	S/N
At transducer terminals	S/N + Directivity Index
At transducer terminals when "optimum" observer detects signal 50% of the time	S/N + Directivity Index Recognition Differential
As above but with non-optimum observer	S/N + Directivity Index Recognition Differential + Observer Loss

Figure 1 - Signal and background in a receiving sonar system

It should be stressed that recognition differential refers to signal detection alone, and not to the other functions which an acoustic system may perform. As mentioned above, the signal-to-background ratio required for these other functions—such as classification or homing—will in general be different from that required for detection. Little attention has been given to these ratios, however, and in what follows we shall be concerned with the detection function alone.

The Optimum Observer - Observer Loss

A necessary, and indeed vital, part of most sonar systems is the human observer, who forms the connecting link between the inanimate sonar system and the purpose which it serves. In defining recognition differential we have tacitly implied that not only is the equipment in its best operating condition, but that the observer is "optimum" as well. By an "optimum" observer we mean a reasonably good, well-trained one, who is alert and free from fatigue. Most laboratory measurements of recognition differentials are made with such optimum observers, for in the laboratory every care is taken to make sure that the observer is excellently trained, alert, and eager to do well.

At sea under operational conditions, however, the observer is seldom "optimum," for obvious reasons. The increase in the signal-to-background ratio required by a nonoptimum observer is called the observer loss. Unfortunately, information on the amount of this observer loss is very limited, despite its importance operationally.

There is some evidence that extensive experience or training is not required for an observer to be "optimum," provided that the task to be performed is a fairly simple one, as is generally the case. At NEL(1), where college students and observers from the Sonar School have been used in laboratory signal-detection tests, it is believed that their performance as observers becomes within 3-4 db of the optimum once the nature of the task is understood. Further, an examination of observers with more than three months experience using QHBa equipment has shown no dependence of performance on their experience(2). Information available as a result of this study on operators with less than three months experience is limited to their tendency to report "false contacts," which was no greater than for experienced observers. False contact reports were found to depend on the individual observer and circumstances, rather than on experience.

On the other hand, when the task to be performed is difficult, continued training is required to maintain peak performance. An example that may be cited is the detection of weak echoes in reverberation, in which the subtle distinctions between reverberation and echo come into play. In this case, a slow and progressive improvement with continued experience has been noted(3, p 222). It was found that if observers were taken off their task of detecting echoes in reverberation for about a week, their performance deteriorated by about 3 db, and that it took another week before they regained their full abilities.

The effects on observer performance of such things as fatigue, general health, and morale would be expected to be substantial. Prolonged audiometer tests on sonar operators and other crew members aboard a submarine have shown a variation in individual hearing from day to day with health and general condition, amounting to a maximum of 10 to 15 db in the case of a head cold or sinus condition(4). Table 1 summarizes the results obtained.

TABLE 1

Condition	Hearing Loss (Audiometer Tests)
Fatigue	
(i) Lack of sleep	No significant variation
(ii) Long sonar watch	About 5 db
Exposure to high-level noise	
(i) As part of routine duties	Permanent loss in high frequencies
(ii) Short term	Temporary loss of 15 db with a gradual recovery, the loss being 5 db after 1 hour
"Hangover"	Some cases improvement of 5 db

Unfortunately it is not clear what hearing loss, as determined by audiometer tests, means in terms of recognition differential(5), although there is some evidence from an analysis of the San Diego County Fair Hearing Survey data that for each 10 db of hearing loss the recognition differential increases by 1 db(59). The above "losses" should therefore not be interpreted as being observer losses, but merely as being indicative of a possible deterioration in detection performance. Possibly the most significant result of this study was that as the tests proceeded

the observers came to realize the importance and significance of the tests, and a "marked" improvement of performance was observed. The interest of the observer in the task to be performed is something that is not easily measured, but it appears to be important in determining recognition differentials. Interest must be maintained; lack of it may result in drastic reductions in detection ability.

The Transition Curve

A curve showing the probability of detection plotted against signal-to-background ratio is called a transition curve. It gives information on the transition in detection probability between signals too small to be detected at all, and signals so large that they cannot fail to be detected. For a given signal-to-background ratio, a point on this curve may be found experimentally by determining the fraction of a large number of independent trials in which the signal is detected. The solid curve in Fig. 2 is a typical transition curve, for a single observation with the signal-to-background ratio plotted in db, relative to that required for a 50% detection probability.

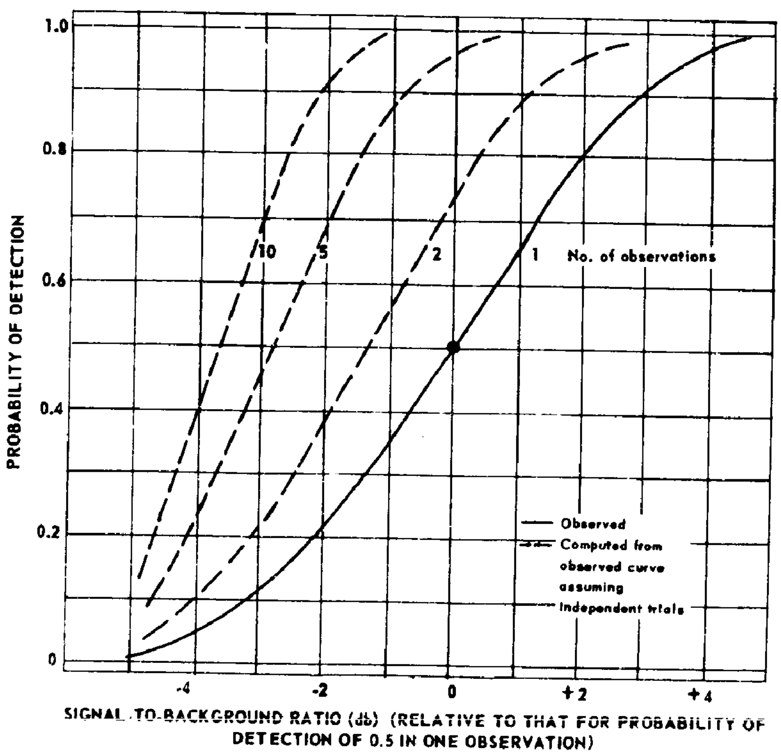


Figure 2 - Transition curves for single and multiple observations

The transition curve provides the correction to the recognition differential required when a detection probability other than 50% is appropriate to the problem at hand. For example, when a submarine echo-ranges off a surface ship to obtain an accurate range for torpedo firing, only a single ping can be used to avoid warning the target. In this instance, a recognition differential of perhaps 90% would be appropriate. An additional correction of a few db would also be necessary in order to allow for the greater signal-to-background ratio needed for ranging relative to that needed for detection.

The single-observation transition curve of Fig. 2 applies to both aural(3,6-8) and visual(9-11) detection systems, and appears to be unaltered whether the background be noise or reverberation. This invariance of the transition curve both to the senses of the observer and to the type of interfering background is most remarkable. It is possible that the transition curve is determined to a large extent by the fluctuations in the background, rather than to any psychophysical characteristic of the observer. This conclusion is supported by theoretical considerations which indicate that the transition curve can be computed from the statistical nature of a random-noise background(12). The importance of background fluctuations in affecting the transition curve is also indicated by evidence that repeated playback of a single recorded signal-plus-noise combination results in little improvement in detection(13). The observer seems to do as well on a single presentation as on a repeated presentation of exactly the same signal and noise, provided he is alert and knows what sort of signal to expect. If, however, the signal is allowed to appear in a different portion of the fluctuating background, as would be the case, for example, with successive pings in echo-ranging, an improvement in recognition differential does occur with repeated presentations. In fact, if the presentations are independent in a statistical sense, so that the observer is not influenced by what has happened before, or if independent observers are used, elementary probability theory shows that the probability of detection in at least one of n repeated observations is $1-(1-p)^n$, where p is the detection probability in a single observation(14). Unfortunately, in practice the observations are seldom entirely independent, and the result serves only as a guide to the possible gain in detection probability that may be achieved in repeated trials.

Transition curves based on the above expression for repeated independent observations are included in Fig. 2. The improvement in detection obtained by using a number of observers was investigated for pure tones and echoes in thermal noise and reverberation using headphones, A-scan presentations, and combinations thereof(14). The observers were provided with separate presentation systems but observed the same signal in background. No systematic differences in the transition curves for 1, 2, or 3 observers were apparent. The use of two observers was found, however, to improve the recognition differential by 1 db, while three observers showed a further improvement of 0.7 db. These values are slightly less than those shown in Fig. 2. It is probable that the full gain to be expected from independent trials was not obtained because the observers tended to detect signals when the fluctuating background was favorable to signal detection. On the other hand, other trials with recorded presentations using the clipper-correlator processing technique showed a progressive steepening of the transition curve as the number of presentations increased(15). For example, the increase in signal-to-noise ratio required to raise the detection probability from 50% to 80% was 7 db with one presentation, but only 2 db with 16 simultaneous presentations. These repeated presentations were not independent, however, and the observed steepening of the transition curves may be the effect of the ability of the observer to "correlate" the presentations.

If we grant that the fluctuation in the background largely determines the shape of the transition curve, we might expect that any reduction in the effective fluctuation, whether obtained by the use of smoothing or long pinglengths, would tend to steepen the transition curve. There is some indication that the transition curve does become somewhat steeper for long pinglengths(6), probably because of the smaller fluctuation in background when averaged over a longer period of time. For example, although 11-millisecond pings required an increase in level of 2.5 db to raise their detection probability from 50% to 80%, the increase required with 270-millisecond pings was only 1.5 db. Filter bandwidths have a similar effect; the use of broadband filters tends to steepen the transition curve(3, p 172). As an example, it was observed that a 3-db increase in signal-to-noise ratio was needed to change the detection probability from 50% to 80% when a 5-cps filter was used, but with a 2800-cps bandpass filter, only a 1.5-db increase was required. Although this effect is probably the result of the greater fluctuation of noise in a narrow filter, it may also be attributed to the distortion of the pulse shape produced by the narrow bandwidth(3, p 172).

Another remarkable feature of the transition curve is that it seems to apply almost, but not quite, as well for listening as for echo-ranging. For listening, the difference in

signal-to-noise ratio between the 80% and 20% levels of detection probability was found from wartime studies to vary from 1.3 to 8 db(3, p 155); the transition curve in Fig. 2 for a single observation gives a difference of 4 db. It is interesting to note that it was believed that the steeper transition curves were associated with over-cautious observers. Nevertheless, a more recent study of the aural detection of submarine machinery noise has indicated that the solid curve of Fig. 2 is typical when listening to such signals(7).

Signal Processing

Since the senses of an observer must, in one way or another, be part of any sonar system, a well-designed system has characteristics which take advantage of the natural and essentially uncontrollable properties of these senses. In order to exploit the properties of the ear and eye, various electronic tricks are employed, ranging from simple amplification to complex techniques such as heterodyning, correlating, and the use of various types of electronic detectors. The purpose of "signal processing"—as these techniques are sometimes called—is to take advantage of the basic properties of the ear and eye.

Another human characteristic, which signal processing exploits when possible, is the ability to remember past events. The ear-brain combination is apparently much inferior to the eye-brain combination in being able to carry over into the future or "remember" something that occurred in the past, such as a marginal signal. This inferior ability to remember aural signals as compared with visual ones may be due to the difficulty of providing a convenient frame of temporal reference. Memory, which permits correlation by the observer between one presentation and another, may be provided by the system itself when some sort of visual presentation is employed by the use of recorded presentations, e.g., the chemical recorder.

The possibilities of assisting detection by signal processing are more limited for aural than for visual presentation. With the ear, the best that can be done is to present the signal to the ear at approximately the level and frequency at which the characteristics of the ear are optimum. In addition to amplification to obtain a comfortable listening level, filtering may be desirable to remove a high-level unwanted background and thereby permit frequencies in the neighborhood of the signal to be presented at an acceptable level. Optimum frequency may be obtained by heterodyning or by frequency-multiplication techniques; the first is common practice with high-frequency signals, while the second has applications to the detection of low-frequency signals(16). As will be seen later, the ear behaves as if provided with a filter network; as a result, filtering before presentation has limited advantages.

When visual presentations are employed, much more can be done by signal processing in providing discrimination against background than with the ear, and an extensive literature on the subject exists(17-26).

The simplest method of signal processing is merely to amplify the signal. The output is then an exact replica of the signal and background, and no discrimination against the background is provided. Discrimination may be achieved by filtering, and when the passband of the filter is sufficiently wide for transient effects to be of no consequence, signal and background within the passband of the filter are again reproduced. Although the level of the background masking the signal is reduced in this way, fluctuations in its level and in that of the signal remain, which mask any small average increases in level due to the presence of a signal. In aural detection, this masking by the fluctuation in level is offset in part by the finite build-up time of the ear, which results in an averaging or smoothing out of these fluctuations, and so assists in the detection of small increases in average level due to the presence of a signal. But if a visual presentation is employed, these fluctuations seriously impair detection of any small increase in average level, whether the presentation employs deflection of a visual trace or spot brightening. It is essential therefore to reduce or smooth out these fluctuations.

In conventional systems this smoothing is achieved by the use of detector (rectifier-averager) circuits. In these systems the incoming signal is filtered (predetection filtering), passed through the detector where it is rectified, and finally passed through a low-pass filter (postdetection filtering). The output is therefore a smoothed rectified envelope of the incoming waveform.

It is of interest to consider the signal-to-background ratio at the output of such detector circuits in terms of the characteristics of the detector and the filter bandwidths. It has been found theoretically for signals and backgrounds with parallel spectra that the output signal-to-noise ratio depends upon the power law* of the detector in the following manner(23):

Power Law of Full Wave Detector	Output S/N Ratio (db) Relative to Square Law Detector	
	Rectangular Filter	Tuned Circuit Filter
1	-0.2	-0.1
2	0	0
4	-0.6	-0.5
6	-2.3	-1.8
8	-4.8	-3.9
10	-8.0	-6.6

The above values apply only for small signal-to-noise ratios, and for small postdetection bandwidths (long averaging times). It will be seen that the square law detector is slightly better than a linear detector, although the difference is small. It has been found that the square law detector has a similar slight superiority in output signal-to-noise ratio when the signal is sinusoidal(27).

It can be shown from theoretical considerations of the fluctuation of "white" noise, that for square law detection of sinusoidal signals the bandwidth of noise effective in masking a signal is the geometric mean of the predetection and postdetection bandwidths, provided the postdetection bandwidth is the smaller(16). This means that the effective masking level of the background increases by 1.5 db for each doubling of either the pre- or postdetector bandwidth. A similar result applies for broadband signals such as propeller noise, provided the signal-to-background ratio is small. In this instance the fluctuation is still largely determined by the background.

We may now consider the effects of the various detector circuit parameters on recognition differential. We have seen that there will be little difference in using linear or square-law detectors. Because recognition differential is defined in terms of the spectrum levels of broadband signals and noise, we must consider the effects of the predetection filter bandwidth on the detection of sinusoidal and broadband signals separately. In the case of a sinusoidal or periodic signal, there is no effect of the filter on the signal level, and the background masking increases 1.5 db for each doubling of the predetection filter bandwidth. Detection will deteriorate, or the recognition differential will increase, at the rate of 1.5 db for each doubling of the predetection bandwidth.** In the case of a broadband signal, on the other hand, the signal level measured in the passband of the filter increases 3 db for each doubling of the bandwidth, while

*If the output voltage V is related to the input voltage v by an expression of the form $V = |v|^x$, then x is the power law of the detector.

**Experimental data for A-scan pulse detection (Fig. 13) confirms that this is the case for bandwidths less than about 200 cps. For larger bandwidths, the increase in recognition differential as the bandwidth is increased is greater than this.

the masking effect of the background increases at a rate of 1.5 db. Detection will improve as the bandwidth is increased, and the recognition differential will decrease by 1.5 db for each doubling of the predetection filter bandwidth.

Decreasing the postdetection filter bandwidth decreases the effective masking and improves detection. For each halving of the bandwidth we should expect a decrease in recognition differential of 1.5 db. That substantial improvements in detection result when the postdetection filter bandwidth is reduced, or the integrating time is increased, is well known(19). It has been shown, for example(19), that for wideband signals with a spectrum parallel to the background the recognition differential of the ear can be approached with a visual system provided the parameters of the low-pass filter are properly chosen.

In the detector circuits discussed above, the envelope of the waveform is utilized for detection, and information on the wave shape itself is discarded, except insofar as predetection filtering is employed to limit the background admitted to the system. Such systems may be called incoherent detectors. In contrast, coherent detectors may be designed which do not extract the envelope, but which utilize the wave shape itself. A coherent detector has been defined(21) as a detector in which the switching of the rectifier is controlled entirely by a pure local oscillation of the same frequency and phase as that of the wanted signal.

The relative merits of coherent and incoherent detectors have been discussed in a number of papers(21,28,29). Complications arise in the case of pulse-detection systems because different criteria of detectability are necessary for different types of display, and because these in turn are subject to different interpretations. Various theoretically derived results for the output signal-to-noise ratio for both types of detector have been reported(21). For small input signal-to-noise ratios $(\frac{S}{N})_{IN}$ it has been found(21) that the output signal-to-noise ratio—when expressed as the ratio of the change in d-c output, on application of the signal to the low-frequency noise when the signal is present—is equal to $(\frac{S}{N})^2_{IN}$ for an incoherent detector, and to $(\frac{S}{N})_{IN}$ for a coherent detector. On the basis of these results it has been concluded that the coherent detector is the better for the detection of pulse signals(21). It should be pointed out, however, that equal performance could be obtained with incoherent detection by the use of multiple filters. Further, coherent detection presupposes knowledge of the frequency and phase of the incoming signal, which are generally not known with sufficient accuracy. Although this difficulty may be overcome by the use of various techniques(21), these involve additional complexity in the equipment, which must be weighed against the use of multiple filters when an incoherent detector is used.

Similar differences in the dependence of output signal-to-noise ratio on input signal-to-noise ratio for coherent and incoherent processing have been reported by others. For example, theoretical formulas have been developed for the output signal-to-noise ratio of correlators when the input ratio is small and the ratio of the input to output* bandwidths $(\frac{W}{w})$ is large(23). For incoherent processing—that is, when both inputs consist of signal and noise—the output signal-to-noise ratio is proportional to $(\frac{W}{w})(\frac{S}{N})^2_{IN}$. On the other hand, when coherent processing is employed—that is, one input consists of signal and noise and the other of signal alone—the output signal-to-noise ratio is proportional to $(\frac{W}{w})(\frac{S}{N})_{IN}$.

During recent years, considerable attention has been paid to correlators as devices to improve the signal-to-noise ratio. Whereas a detector is essentially a rectifier followed by a low-pass filter, a correlator is a multiplier, also followed by a low-pass filter. A correlator usually requires two samples of signal and noise, so that they can be "correlated" with one another, or more properly, one sample multiplied by the other, and averaged. A detector, on the other hand, requires but one sample of signal and noise. The two samples required for correlators can be the outputs of two nearby hydrophones or the two halves of a split transducer, or even a single sample plus that same sample delayed in time (autocorrelation). Much

*Output bandwidth $w = 1/t$ where t is the averaging time RC of the low-pass RC filter.

has been written about the relative merits of correlators and detectors. Perhaps the best quantitative statement is contained in a paragraph from a recent report(23). "The results above show that if two samples of the same signal in incoherent background noises are available, the correlator can produce a signal-to-noise ratio 3 db better than that of the square-law detector operating on one sample of signal in noise. Obviously if two samples of the signal in incoherent noises are available, they can be added and applied to the square-law detector, where with the input signal-to-noise ratio increased by 3 db, the output signal-to-noise ratio will be increased by 6 db, a result 3 db better than for the correlator. The correlator, on the other hand, produces no d-c output independent of the signal, a practical advantage that should not be overlooked."

Many complicated schemes for signal processing have been proposed and employed in recent years. Most of these contain elements of detectors and correlators, or both. Some of them which have been built and tested are the periodmeter(55), dating back to World War II, the sector-scan indicator (SSI)(25), the range-rate indicator (RRI)(57), the clipper-correlator(15), and the axis-crossing interval meter (ACIM)(58). The reader is referred to the literature for the performance of these and other devices.

AURAL DETECTION

Characteristics of the Ear

The ear has certain well-known properties that make it extremely suitable for detecting signals in an interfering background, and the Navy has used listening in underwater sound ever since the German U-boat was found in World War I to be detectable by the sound it produced. The nature of the auditory sense has been studied by a host of investigators for many years, and a truly enormous literature on audition in all its aspects is available. Much of it applies directly or indirectly to the subject of recognition differential. In what follows, only the more useful aspects for underwater sound will be summarized, and the reader must refer to the literature for information on other topics.

Optimum Listening Level—In listening to signal and background, it is obvious that signal and background must be neither too faint to be heard, nor so loud that discomfort is felt by the listener. Thus there must exist a listening level at which the loudness of the presented sound is optimum for best detection performance.

The loudness of sounds of different frequency is given by a well-known diagram (Fig. 3) showing contours of equal loudness(15). These extend from the threshold of hearing up to the threshold of pain. The apparent loudness of a tone varies with frequency; tones of about 1000 cps appear louder than tones of equal intensity at the ends of the audible range.

Experiments show that most observers prefer a loudness* of about 70 phons(3, pp 87,231). This level is not critical, although departures from it of 20 phons have been shown to cause a deterioration in detection performance(3, p 231). The fatigue produced by a nonoptimum loudness level seems to be a most important factor, even though the recognition differential may be somewhat improved when levels higher than optimum are presented to the observer for a short time. Obviously, when an observer listens for a long period of time, his comfort must play a large part in determining his recognition differential.

Build-Up Time—The apparent loudness of acoustic signals is also a function of their duration. Short pulses do not sound as loud as long pulses; pulses shorter than about 1/4 second show a marked decrease in loudness. This effect is attributed to the finite build-up time of the

*The loudness level of a tone, expressed in phons, is equal to the level of a 1000-cycle tone which appears to be equally loud as the tone in question.

ear, as though the ear required a certain persistence of stimulation to reach its full response(3, p 32). At normal listening levels, for example, the loudness of a sustained tone is about 15 phons higher than that of a pulse of 5 millisecond duration at the same pressure level; the difference decreases as the threshold of hearing is approached. The build-up time of the ear is most important for the detection of pulses, as will be discussed below.

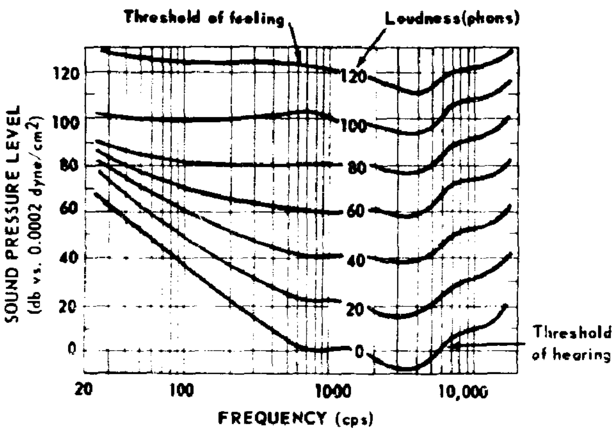


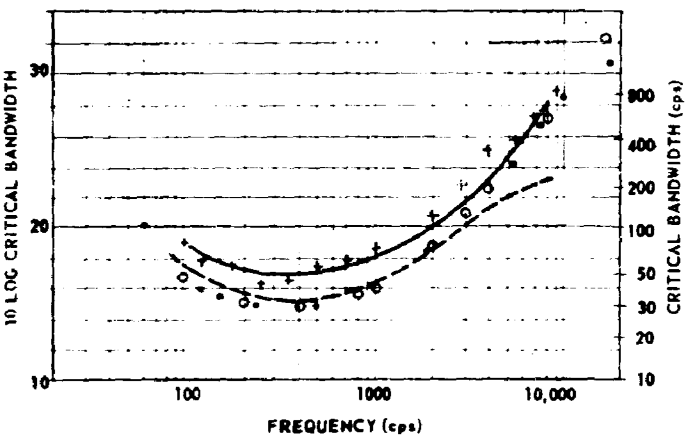
Figure 3 - Aural equal-loudness contours for tones. The sound pressure levels are free-field levels before entry of the subject. (From Fletcher, Ref. 30.)

Critical Bands—The ear also behaves as if it were provided with a series of contiguous bandpass filters. These so-called critical bands are perhaps the most important characteristic of the ear for the detection function, for in making the detection decision the ear appears to be able to select that particular filter in which the signal-to-background ratio is highest.

The critical bandwidths are usually determined by presenting to a listening observer signal and wideband noise through a variable bandpass filter. As the bandwidth of the filter is reduced, it is found that the level of a just-detectable signal remains unchanged, until the "critical" bandwidth is reached—below which the just-detectable signal level decreases with narrowing bandwidth. This is just what would occur with two filters in series; in analogy, the ear is said to act as though it had a filter of its own with a bandwidth equal to the critical bandwidth. Critical bandwidth determinations by various investigators(31) are given in Fig. 4 for listening with one ear and with two ears. Those of French and Steinberg(32) for the two-ear case, which is the more appropriate for sonar detection, have been recently confirmed at NEL(1).

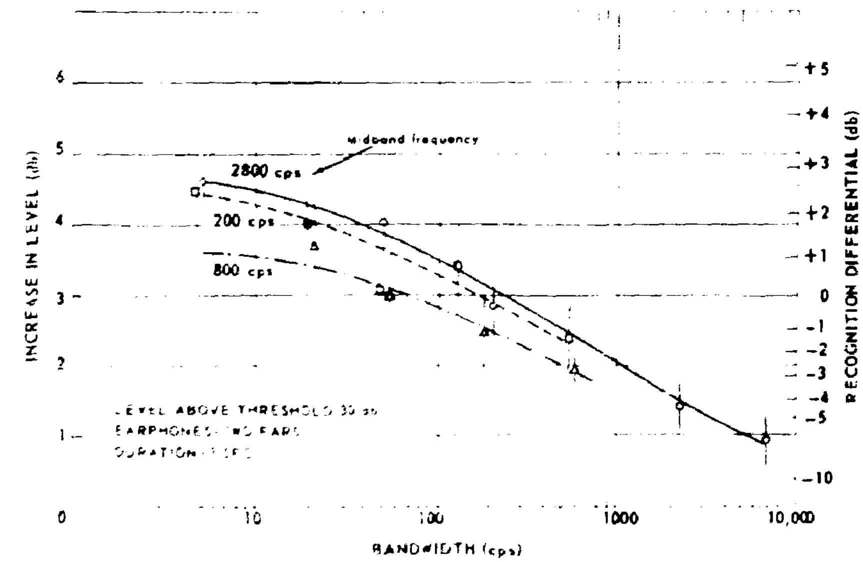
An implication of the critical band concept is that a tone in one critical band does not interfere with, or "mask," a tone which falls in another, unless the interfering tone is very strong. The critical bands are thus effectively independent of one another. This property of the ear is most important in determining recognition differentials, and gives rise to the "critical band rule" to be discussed below.

Sensitivity to Changes in Level—The ear's ability to detect changes in level of a wideband continuous spectrum is of interest when a signal has a continuous spectrum parallel to that of the background, as may be the case with propeller noise. At best the ear's sensitivity to changes in level of wideband noise is about 0.5 db(33), implying a recognition differential of -9 db. For practical purposes, however, the minimum detectable change in level is probably about 1 db(19), corresponding to a recognition differential of -6 db. The minimum increase in level in wideband noise which can be detected depends upon the bandwidth of noise presented to the ear, and upon the frequency at which that bandwidth is centered. Figure 5 shows the sudden increase of level of random noise perceptible in 50% of the number of trials, as determined by recent measurements(31). It seems likely that the increased sensitivity of the ear to changes in level as the bandwidth is increased is due to the smaller fluctuation of noise in the increased bandwidth(31).



○ One ear; Fletcher, J. Acoust. Soc. Am., Vol. 9, p. 285 (1938)
• One ear, Fletcher, Proc. Nat. Acad. Sci., p. 265 (1938)
+ One ear; Hawkins & Stevens, J. Acoust. Soc. Am., Vol. 22, p. 10 (1950)
—— One ear; French & Steinberg, J. Acoust. Soc. Am., Vol. 19, p. 96 (1947)
– – Two ears, French & Steinberg, J. Acoust. Soc. Am., Vol. 19, p. 96 (1947)

Figure 4 - Aural critical bandwidths as a function of frequency for one and two ears (From Gales, Ref. 31)



[illegible] of random noise
[illegible]

Modulated Signals—The equal loudness contours of Fig. 3 pertain to steady tones. When a tone or noise is interrupted or is amplitude modulated, the interrupted signal appears to be louder than the corresponding signal of the same peak amplitude, as long as the rate of modulation is less than about 30 per second(33). Maximum loudness is obtained when the modulation rate is between 1 and 10 per second.

Of direct interest in listening to submarine sounds is the recognition differential for amplitude-modulated, wideband noise signals. In one laboratory study, the effect of modulation rate on the detectable increase of level, expressed as the ratio of peak to minimum levels, was studied for square-topped modulated noise (Fig. 6)(33). For low modulation rates, up to about 10 per second, the detectable change in level was found to be 0.5 db. At repetition rates higher than 10 per second, the detectable change in level increased with increasing repetition rate. Earlier laboratory work(34; 3, p 33-34) had shown a somewhat similar behavior for sinusoidally modulated tones, except that slow sinusoidal modulations were more difficult to detect; the detectable increment of level had its minimum value at a modulation rate of about 4 per second. Thus, the sinusoidal and square-topped forms of modulation appear to be similar at high modulation rates where the ear perceives a tone at the modulation frequency, but not at low modulation rates where the sudden increase and decrease of level with the square-topped form enables the ear to detect smaller changes in level.

Duplex Presentation—Masking of sounds in one ear by sounds in the opposite ear is not appreciable unless the level of the sound in one ear exceeds that in the other by about 40 db. Each ear should be capable, therefore, of monitoring a completely separate system. Minor changes in recognition differential might be expected from the difference in critical bandwidths for one and two ears, as shown in Fig. 4. It has been found for simulated echoes in noise and reverberation backgrounds that a single observer can monitor two channels in this manner(31). Changes in the observed recognition differentials differed by less than 1 db from the normal case where both ears monitor a single channel. No difficulty was encountered in determining which channel contained the signal.

Binaural Presentation—In the binaural system, each ear monitors a separate receiving hydrophone, the two hydrophones being placed in the water a distance apart in analogy with the separation of the two ears. Despite the attention given to this type of system, it is not too clear exactly what gains result in terms of recognition differential. It appears that the gain is small, amounting to perhaps 2 db. Such a gain has been reported by NEL for a system which was circuit-noise limited(8). A review of available information on this subject(12,35) has concluded that the improvement in signal-to-noise ratio resulting from binaural presentation is no greater than could be achieved by the simple addition or subtraction of the signals from the two hydrophones and normal presentation to the two ears. However, binaural listening does permit greater bearing accuracy to be achieved.

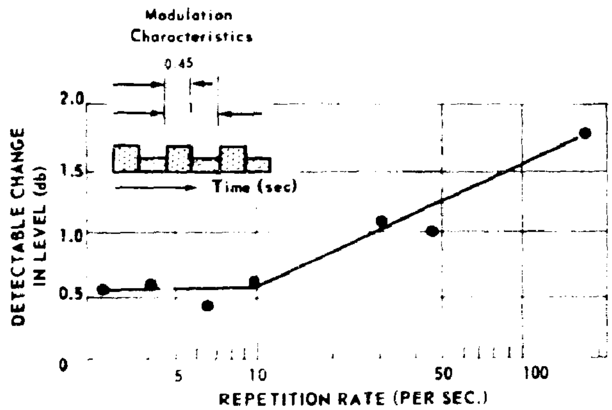


Figure 6. Aural detection of modulated noise (From Pollack, Ref. 33)

Multifrequency Presentation—Because of the frequency discrimination of the ear, it should be possible for an observer to listen on several channels simultaneously. By monitoring two

or more directional transducers in this manner, for example, an observer may be able to listen in several directions simultaneously. An example of the use of this technique is the so-called Multiple Aural Scanning Equipment developed by USL to increase the search rate of a scanning sonar(36). The criterion for successful multifrequency presentation is that the different channels must be presented to the observer in different critical bands. Because there is no masking of the signal in one critical band by the background in another, the recognition differential should remain unaltered. That this is actually the case has been shown by NEL for pulses in noise backgrounds(37). It was also found that the particular channel in which a signal occurs can be identified, as long as the presentation frequencies are widespread and have no harmonic relationship. Thus, it was found that four channels could be monitored simultaneously when the frequency spacing between channels was 700 cps, but not when the spacing was 200 cps, because of difficulty in identifying the channel containing the signal.

When the background is reverberation rather than noise, higher signal-to-background ratios are required for detection with multifrequency presentation. For three channels spaced 700 cps apart, the recognition differential for reverberation is about 4 db higher than for a single channel(1). The reason for this is not apparent, although it must be related to the characteristic "blobbiness" of reverberation.

Earphones vs. Loudspeakers—Provided an observer is in a quiet situation, there is no significant difference in the recognition differentials obtained with earphones and with loudspeaker systems of good design. In noisy situations, some advantage would be expected in using earphones in order to shield the observer from local room noise, which would otherwise contribute to the masking background.

System Distortion—In discussing aural detection we have assumed that the acoustic signal presented to the observer suffers no distortion in passing through the detection system. It might be expected that distortion of the signal could in some cases assist in detection and result in lower recognition differentials. Although information on the effects of distortion is limited, it appears that distortion must be considerable before the recognition differential is affected(3, p 198,232). In these wartime tests, detection of pulses in noise and reverberation was studied under conditions of severe distortion, involving rectification and transmission of less than half of each cycle. Detection was found to deteriorate with severe distortion, although the increase of recognition differential was but 3 db at most.

Detection of Continuous Signals

Most problems in the passive detection of underwater sounds pertain to sound sources driven by rotating machinery, such as ships, submarines and torpedoes. The spectra of these sources of underwater sound consists of a continuous spectrum due largely to cavitation, on which a line spectrum due to machinery is superposed. The discontinuous nature of the spectrum is its principal feature at low frequencies. The background in which the signal appears may be similar to the signal when its principal component is self-noise, or it may be totally dissimilar, as when the background is ambient noise at low frequencies. A further characteristic of the sounds from propeller-driven sources is the modulation of the radiated sound produced by the rotating propeller.

Having stated in preceding sections a few of the important properties of the ear for aural detection, we shall in what follows discuss the application of these properties to the detection of ship and torpedo sounds.

Sonic Listening - Steady Signals—We have seen that the ear behaves as if provided with a large number of adjacent and overlapping filters. These so-called critical bands are determined by the masking properties of the ear, and make possible the prediction of recognition differentials for simple and complex signals.

The detection of steady signals is determined by the critical-band rule, which states that detection occurs when the level of the signal is equal to that of the background when both levels are measured in a critical band.

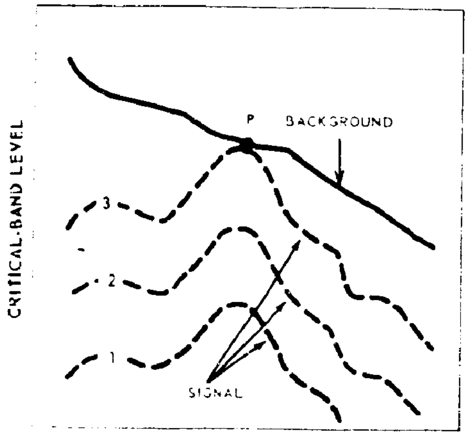


Figure 7 - Spectra illustrating the critical-band rule. As the signal increases, it becomes first detectable at the level and frequency of point P, at which the critical-band levels of signal and background are equal.

The rule is best illustrated by means of a diagram. In Fig. 7 the spectra of signal and background are plotted as levels in the critical band at the particular frequency, rather than as spectrum levels. The critical-band rule states that as the signal is increased(1...2...3), detection first occurs at the level and frequency at which the signal and background are equal (curve 3).

The validity of this rule for actual underwater sounds has been demonstrated by the results of wartime listening studies(3, p 154) and by a more recent study of the detection of auxiliary machinery sounds in simulated ambient noise(7). In this latter study, recognition differentials computed by the critical-band rule from the spectra of machinery and ambient noise were found to be on the average within 2 db of experimentally determined values.

When using the sonar equations it is necessary to determine the recognition differential for a signal in a background when their spectra are given. Recognition differentials will now be derived from the critical-band rule for various spectral components of a signal. It will then be shown how the appropriate recognition differential can be selected.

For a strong line component, detection will occur when the level of the component is equal to the total level of the spectrally continuous background lying in one critical band at the line component's frequency. This total level is equal to the spectrum level of the background plus ten times the logarithm of the critical bandwidth; accordingly the aural recognition differential for a nonfluctuating, single-frequency sound is + 10 log W_{CB}, where W_{CB} is the width of the critical band at the signal frequency. We shall see that if the signal is modulated, the recognition differential is lower than this by up to 3 db, depending on the degree of modulation.

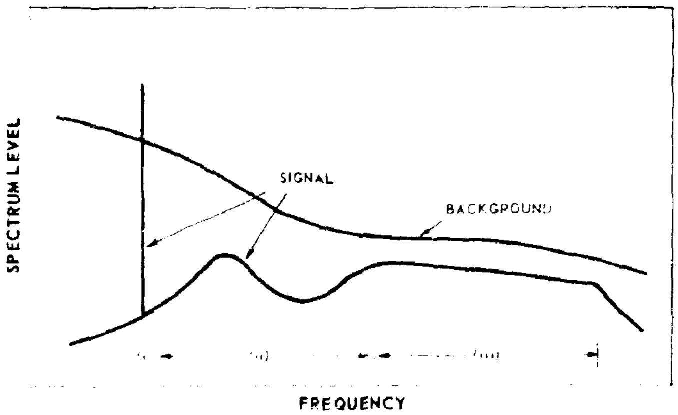
The use of filters narrower than the critical bandwidth is obviously of advantage in detecting single-frequency sounds with the ear. One might expect that with a filter of bandwidth W_F, narrower than the critical bandwidth, the recognition differential would be improved by 10 log (W_{CB}/W_F), or at the rate of 3 db per octave of decreasing filter bandwidth. However, measurements of the detection of long pings in noise (See Fig. 10 on page 20) show that the improvement is but 1.5 to 2.0 db per halving of the filter bandwidth. The discrepancy is probably attributable to the increasing fluctuation of the background as the filter bandwidth is decreased. It is difficult to take advantage of this gain from the use of narrow filters when listening, since it is generally necessary to cover a wide range of frequencies. One approach is to use so-called comb-filters, which have been found to give an improvement in recognition differential of about 7 db over the unaided ear for 300- and 1000-cps tones when the filter bands were 5 cps wide(12,16).

For the continuous spectrum of a signal, application of the critical-band rule shows that the recognition differential is zero because neither the spectrum level of signal or background change appreciably within a critical band

An exception to the critical-band rule occurs when the spectra of signal and background are parallel over several to many critical bands. Here the ear probably detects the signal by means of the increase of level. The recognition differential decreases, and detection improves, as the frequency range over which the spectra are parallel is increased, and Fig. 5 should apply. It should be pointed out that filtering would impair detection in such cases.

Similar small improvements in recognition differential may be expected when the equality of signal and background occurs simultaneously in a small number of critical bands, as with a signal containing several line components equally strong relative to the background at their particular frequencies. For example, Fig. 5 indicates that for three critical bands (bandwidth approximately 120 cps) the decrease in recognition differential should be about 1 db.

With complex spectra, in order to select the correct recognition differential for use in the sonar listening equation, it is first necessary to determine which feature of the signal will be detected first as the signal level is raised relative to the background. The principal features of a signal of importance in detection are indicated in Fig. 8. Appropriate recognition differentials summarized in Table 2 are included in this figure. Each part of the signal will be detected when its level exceeds the background level by an amount equal to its particular recognition differential. As the level of the signal is increased relative to the background, detection will occur first at that part of the signal spectrum or frequency where the level first exceeds the background level by the appropriate recognition differential. Signal and background levels at this frequency should be used in the sonar equation together with the recognition differential for the feature which is detected. Signal and background levels will be spectrum levels unless a line component is first detected, when the level of the component should be used.



(a) Line Component — Recognition Differential 10 log W
(b) Continuous Spectrum — Recognition Differential 0
(c) Continuous Spectrum parallel to background. — Recognition Differential 0 to −6 depending on frequency range over which parallel see Figure 5

Figure 8 - Application of the critical-band rule to the detection of complex signals

It will be noted that in order for a line component in a signal to be significant in detection, its level must exceed the spectrum level of the spectrally continuous part of the signal at its frequency by at least 10 log W_{CB}. Similarly the levels of line components in the background which may occur when the background is self noise, must also exceed the continuous background spectrum level by this amount if such line components are to be significant in masking the signal.

Sonic Listening - Modulated Signals—Signal modulation may be inherent in the signal, as in the case of propeller cavitation noise, or may even be induced by rotation of the receiving transducer. For relatively slow modulation rates modulation appears to assist detection because signals are detected by the ear at the peak level of the modulation. Strictly speaking, however, this improvement is a result of the modulation being slow enough for the ear to detect the peak level; slow modulation *per se* does not improve detection.

The validity of the dependence of the detection of modulated single-frequency peaks, or line components, on their peak level was established as a result of wartime tests(3, p 154). It was concluded that the critical-band rule could be applied to single frequency peaks modulated in level at rates up to about 5 per second, provided the peak level of the signal was used. The recognition differential for a steady line component must be corrected, therefore, for the difference between peak and rms levels in order to apply to a modulated signal. The recognition differential for a slowly fluctuating, fully-modulated line component is therefore 10 log W_{CB} -3db.

It was also concluded as a result of these wartime studies(3, p 154) that detection of a wideband modulated signal, the spectrum of which parallels the background, occurs when the total modulation of the signal and background mixture is 1 db*, provided the modulation rate is between 1 and 10 per second. It can be shown (3, p 107) that this corresponds to a recognition differential of -9 db for a fully modulated signal, and to a recognition differential of -8 db for a signal which is 50% modulated. A more recent determination(38) of the recognition differential for submarine propeller noise has been made by NRL in connection with the development of sonobuoy presentation systems. A value of -9 db (standard deviation 2 db) was found, in good agreement with the earlier studies.

Analysis of the possibility of detecting amplitude-modulated white noise by square-law rectification and bandpass filtering at the modulation frequency has shown that smaller depths of modulation may be detected by this means than by the unaided ear(12,39). It was found that a 5-db improvement in the detection of modulated cavitation noise may be realized, with a 10-second signal observation time and with post-detector filters of 1/10-cps bandwidth(39). A frequency multiplication of 500 obtained by recording and playback at high speed was used to obtain this bandwidth.

Ultrasonic Listening—When ultrasonic listening is employed, the high-frequency signal and background received by the sonar system are heterodyned to frequencies in the audible region where the characteristics of the ear are most favorable for detection. Heterodyning results purely in a shifting of all frequencies in the received signal and background by a constant amount.

Detection of ultrasonic sounds from a variety of ships and submarines was studied by UCDWR during the war(3, p 117-122). It was found that the signal-to-noise ratio for detection had to be -1 db (average deviation 1 db) in the optimum 50-cps band, which approximated the critical bandwidth at the frequency of presentation to the observer. That is, the critical-band

*Figure 6 indicates that the ear can detect a smaller modulation than this. One db is a practical limit with normal signals and backgrounds.

TABLE 2

Aural Recognition Differentials - Continuous Signals

Signal	Recognition Differential (db)		
	Steady Signal*	Fully Modulated Signal	Effect of Reducing Filter Bandwidth
Line component	10 log W_{CB}	10 log W_{CB}-3	$W_F > W_{CB}$, No change $W_F < W_{CB}$, Recognition decreases by 5 log $\frac{W_{CB}}{W_F}$
Broadband signal with spectrum not parallel to background in more than one critical band	0	-3	$W_F > W_{CB}$, No change $W_F < W_{CB}$, Small increase
Broadband signal with spectrum parallel to background over several or many critical bands	0 to -6†	-3 to -9†	Recognition differential increases

*In the case of ultrasonic listening these values apply whether the signal is modulated or not.

W_F = Filter Bandwicth

W_{CB} = Aural Critical Bandwidth

†Depending on frequency range over which spectra parallel—see Fig. 5.

rule applied. In most instances the signals were wideband, with spectra approximately parallel to the background. On the average the over-all level of the signal for detection was 3 db below that of the background. In the tests the passband was about 1400 cps. for which a recognition differential of -3 db would be expected for steady signals (see Fig. 5). The signals studied exhibited a variety of modulation but no correlation was observed between the signal modulation and the recognition differential. This suggests that the signals were detected at levels appropriate to steady signals. It appears from these tests therefore that ultrasonic listening is inferior to sonic listening. This result confirms the opinion of observers that ultrasonic signals have little character and are more difficult to detect than sonic signals(3, p 120).

Subsonic Listening—In contrast to the use of heterodyning to transpose signals from one frequency to another, frequency multiplication may be employed. Frequency multiplication, which may be achieved by recording and playback at higher speed, is particularly suited to the aural detection of low-frequency line components. That this should be the case can be shown from the critical-band rule. For although the signal level is unaltered on multiplication, the level of the background in a critical band is reduced. This reduction takes place in two ways. First, the critical bandwidth itself decreases with increasing frequency at low frequencies, Fig. 4. Second, the background in a bandwidth W is spread out over a frequency range mW on multiplication, where m is the multiplication factor. Results of one study of this technique have been reported(16). It was found that when the frequency was multiplied by 4, a reduction in the recognition differential for a 200-cps tone of 4 db was obtained. This was somewhat less than the expected reduction of 6 db, but the agreement was probably within the experimental error(16).

Detection of Pings in Noise Backgrounds

Echo-ranging is primarily concerned with the detection of sound pulses or "pings" rather than with the continuous target sounds of interest in listening. Echo-ranging pings are usually of constant amplitude and frequency, although various forms of modulation, such as frequency modulation, have sometimes been employed.

The aural recognition differential for pings received considerable attention during World War II and subsequently, and our knowledge of the subject is consequently rather complete (3, pp 170-208). However, nearly all the investigations of the subject have been confined to idealized echoes generated in the laboratory and to recorded beam-aspect echoes, and unfortunately little is known about the recognition differential for off-beam echoes characterized by an irregular ping envelope. Also, very little attention has been given to the determination of the recognition differential of f-m pings, noise pings, or of the other types of modulation that are possible.

Effect of Pinglength—Figure 9 presents a smoothed summary of available data on recognition differential as a function of pinglength. For long pings the recognition differential should be the same as in the case of listening, namely 10 log W_{CB}, where W_{CB} is the critical bandwidth at the ping frequency as presented to the ear. As the pinglength is reduced below the build-up time of the ear (about 250 milliseconds), the recognition differential should increase. An additional increase of recognition differential with decreasing pinglength is probably important for pings of such short duration that their spectra cover several critical bands of the ear(3, p 192). These features can all be found in the curves of Fig. 9.

These curves apply to pings with smooth envelopes. They apply to target aspects such that the return of sound back to the source is principally by specular reflection. When the envelope of the ping is irregular, as is usually the case, the validity of the data has not been directly determined, although it is likely that Fig. 9 is applicable if the actual echo length is employed, and if the signal level is expressed as the average, rather than the peak, echo level.

Effect of Frequency—The frequency at which an echo is presented to the ear also plays a part in determining the recognition differential, as shown in Fig. 9. The effect is greater for

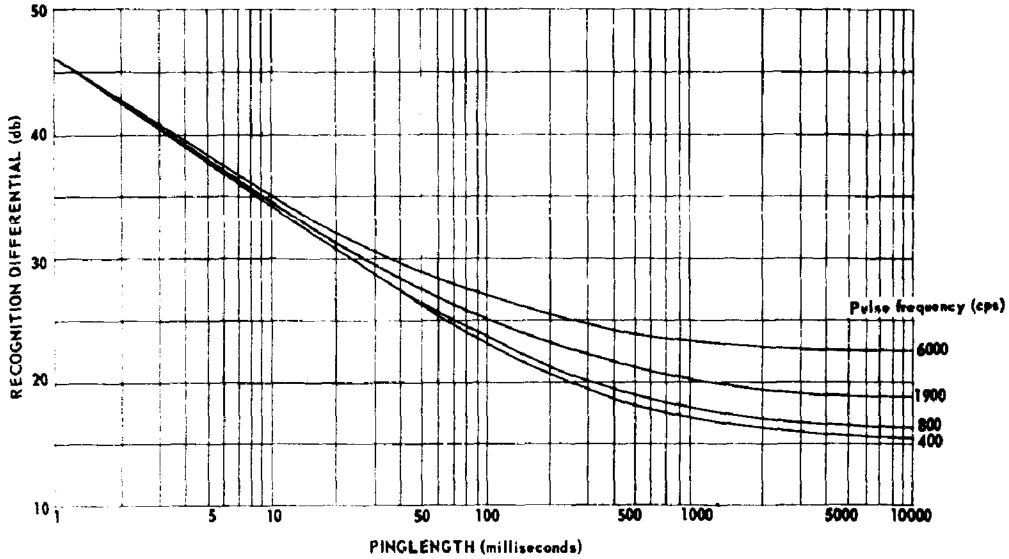


Figure 9 - Aural recognition differentials of pings in wideband noise, based on curves provided by NEL (Feb. 1953) which were derived from data given in:

(a) "Recognition of Underwater Sounds," NDRC Div. 6 Summary Technical Report, Vol. 9, pp. 189, 195 (1946)
(b) Garner & Miller, J. of Exper. Psychol., Vol. 37, p. 297 (Aug. 1947)
(c) French & Steinberg, J. Acoust. Soc. Am., Vol. 19, p. 96 (1947) (aural critical-band data for two ears)

long pinglengths than for short, as might be expected from the fact that short pings have no definite tonal quality(3, p 194).

Effect of Bandwidth—If filters narrower than the critical bandwidth are employed, the recognition differential for pulses should decrease, i.e., detection should be assisted since the background level will be reduced. This gain is offset in part by the increased fluctuation in noise level as the bandwidth is reduced. Available experimental data(3, p 172,40) on the effect of filter bandwidth is presented in Fig. 10. Reduction of the filter bandwidth results in a decrease in recognition differential of 1.5-2 db for each halving of the bandwidth. The recognition differential tends to reach a minimum value when the bandwidth-pulselength product is unity, that is, when the frequency spread of the pulse is such that the filter begins to limit the pulse energy transmitted.

Modulated Pings—It might be expected that the use of either amplitude or frequency modulation in a pulse would provide an observer with an additional cue for detection. Few determinations of the recognition differential for such pulses have been reported. In wartime BTL tests it was found that the recognition differential for an amplitude modulated pulse, consisting of two 200-millisecond pulses separated by 200 milliseconds, was 3 db less than for a single 200-millisecond pulse; that is, it was the same as for a 600-millisecond pulse(3, p 182). Other investigations have dealt with the detectability of repeated pulses such as those employed by fathometers installed on submarines(3, pp 200-208).

It appears that in general the recognition differentials for frequency-modulated pulses are somewhat higher than for tonal pulses of equal duration(3, p 182-185). Provided the pulse

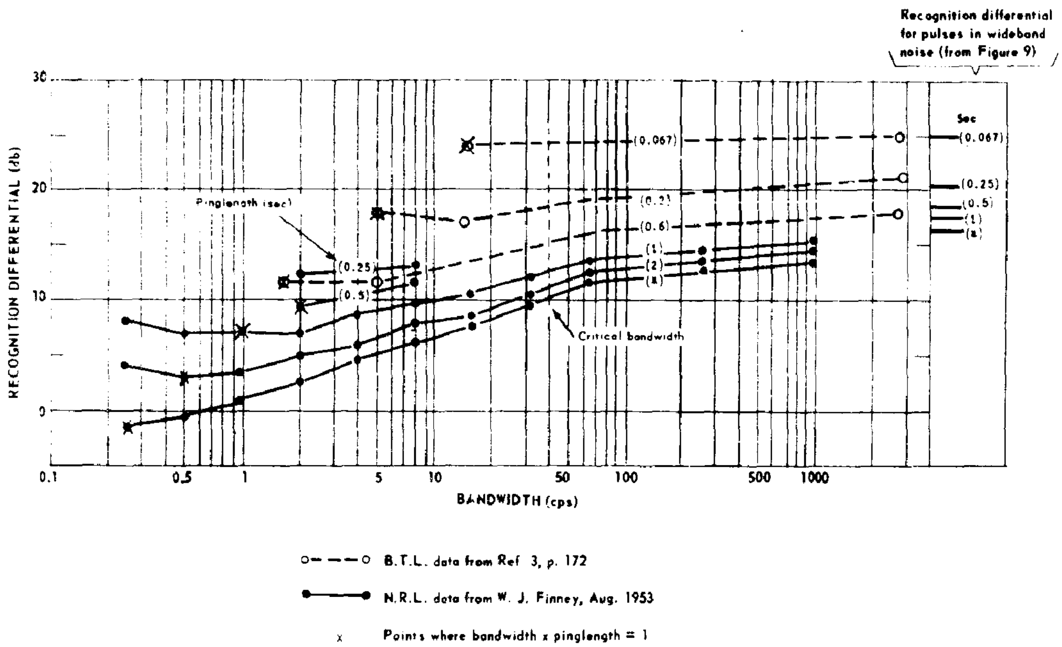


Figure 10 - Effect of receiver bandwidth on aural detection of 800-cps pings in noise

length is reasonably long, say 100 milliseconds or more, and the frequency sweep is not excessive, the difference in recognition differential is small,* and can probably be accounted for by the variation in critical bandwidth for the various frequencies in the pulse. For pulses of duration less than 30 milliseconds, the differences may be greater, and field tests with 10-milliseconds pulses tend to support this conclusion(3, p 184). Although the recognition differential for frequency-modulated pulses are probably inferior to those for c-w pulses of equal duration, frequency-modulated pulses have some advantages in that they appear to be easier to distinguish from false cues in the background(3, p 185).

Repeated Presentation—It has been noted that an observer gets almost all he can from a single presentation, and that repeated presentation of the same signal in the same background results in little gain. On the other hand if the background sample varies from presentation to presentation, the improvement in detectability shown by the transition curves for repeated trials (Fig. 2) may be expected. Decreases in recognition differential of 1.5 db for each doubling of the number of presentations have been reported in this case(41) It should be noted, however, that memory was provided by allowing the observer to mark a blank range recorder when he believed a signal might be present, and this may have contributed to the improvement.

Detection of Pings in Reverberation Backgrounds

Reverberation is essentially different from noise in that its spectrum is confined to a narrow band of frequencies centered at the frequency of the emitted ping, shifted by the amount

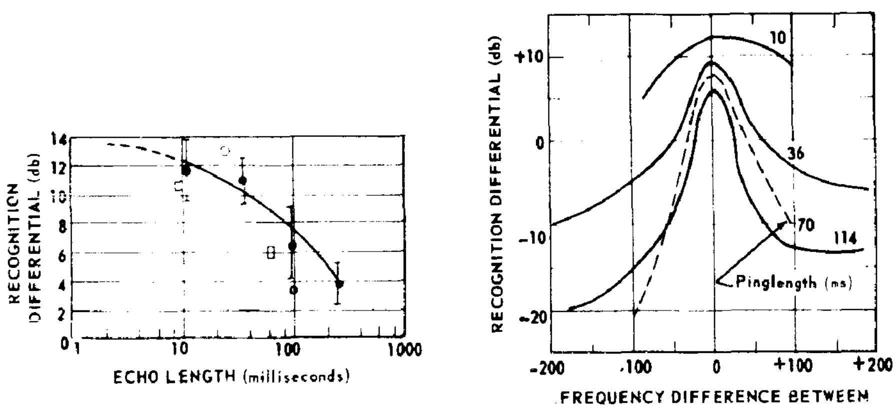
* [illegible] pulse with a frequency sweep of 400 to 2500 cps, the recognitional [illegible] higher than [illegible] tonal pulse of this duration.

of the doppler shift due to the motion of the sound source and the reverberating scatterers. Its envelope is a series of "blobs" which are more or less exact replicas of the envelope of the emitted pulse.

If neither the sound source nor the scatterers are in motion, it would be expected that the spectrum of reverberation would be exactly the same as that of the emitted pulse. Motion of the scatterers causes a broadening of the reverberation spectrum, as does the beamwidth of the transducer if it is moving. But the principal difference in the spectra of emitted ping and reverberation is the well-known doppler shift due to the motion of the source. If the target also is in motion, the echo will be altered in frequency by the additional amount of the doppler shift due to the moving target. The frequency difference of echo and reverberation has a great effect on the recognition differential of echoes in reverberation backgrounds, especially when echo and background lie in different critical bands of the ear.

The subject of recognition differential for pings in reverberation received a great deal of attention during World War II(3, pp 209-259). Since that time little additional work has been undertaken, and our knowledge of the subject remains substantially the same as it was at the end of the war.

Figure 11 shows the recognition differential of pings in reverberation backgrounds for different pinglengths and doppler shifts(3, p 224,254). These curves were obtained by injecting ideal pulses, or recorded beam echoes, in recorded reverberation backgrounds and observing the echo-to-reverberation ratio for a 50% detection probability.



● 800-cps beam echoes, reverberation level at echo mid-point

○ 800-cps pings, reverberation level at echo mid-point

□ 1000-cps pings, reverberation level that of peaks in neighborhood of signal

10 & 70 ms - British data
1000 cps, listening level 80 db

36 & 114 ms - UCDWR data
800 cps, listening level 60 db

(a) No doppler

(b) Doppler present

Figure 11 - Aural recognition differentials for echoes in reverberation (From Ref. 3, pp. 224, 254)

There appears to be no information on the detectability of off-beam echoes of irregular envelope, and of a duration longer than that of the emitted ping. There is also no data on the recognition differential of pings longer than 300 milliseconds, which are of practical utility in long-range active search.

Pinglength and doppler shift are the principal parameters affecting the detectability of echoes in reverberation. The importance of other variables was studied during the war.

Examples are the effect of loudness level, distortion of signal and reverberation, an advance knowledge of the target range, heterodyne frequency, and loudspeaker presentation versus headphones. These effects were all found to be small or negligible.

VISUAL DETECTION

"Although audio detection in sonar and visual detection in radar have been studied extensively, comparatively little work has been done on visual detection in sonar, and virtually no attention has been given to the combination of audio and visual presentations." This statement from a recent report(41) is surprising, since visual presentations have been used in fleet sonar equipment* for many years. It is indicative of the state of our knowledge of the recognition differentials of systems employing visual presentations.

It has been stated above that when visual detection is employed, the potentialities of signal processing are considerably greater than when aural detection is used. This in itself is a complication in discussing and obtaining visual recognition differential data, for signal processing prior to the presentation must be considered in addition to the psychological aspects of detection of a signal in a background. Further, the characteristics of the presentation device itself introduce additional factors affecting detection. For example, when the presentation device is a cathode-ray tube(42), bulb wall reflections, screen curvature, halation, and the use of nonreflecting glasses or metal-backed screens affect the contrast, and even the characteristics of the phosphor itself are of considerable importance(42).

In general, it is impossible when discussing signal detection to separate signal processing from presentation. Innumerable systems have been studied in recent years, and various methods have been proposed to provide improved performance(43). But the treatment has in general been qualitative, and quantitative data—in particular recognition differentials—are only rarely available.

A-Scan Presentation

A cathode-ray tube provides three useful dimensions for the presentation of signal information: two space coordinates, and the intensity or brightness of the trace. A fourth dimension may be added by the use of stereo display systems(43,44). In the normal A-scan, use is made of the two space coordinates to present signal and background as a function of time, which in echo-ranging is equivalent to a plot of signal and background versus range. Although fairly extensive studies have been made of the effect of various electrical parameters on A-scan detection for radar(42,45,46), and similar more limited studies have been made for sonar(41,47, 48) the psychological processes involved in such a presentation (for example, judgment of the length of lines, etc.) have never been intensively analyzed(42).

A-Scan Detection of Pulses in Noise—If no nonlinear circuits are employed, an A-scan presentation is an exact reproduction of signal and background at the terminals of the transducer as function of time (Fig. 12a). On the other hand, if detector circuits are used, the signal and background are rectified and integrated, and a smoothed envelope is presented (Fig. 12b).

It is generally recognized that fluctuations in background level during a presentation tend to mask a marginal signal, and an integrated presentation should therefore result in improved detection. The following recognition differentials(44) for 500-millisecond single-frequency pulses in noise having a bandwidth of 213 cps support this conclusion, but suggest that the effect is relatively small in this instance:

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*For example, PPI presentation in QHB, and chemical recorders on searchlight equipments.

Integrated A-scan (Fig. 12b) (integration time 0.5 sec.)	14.5 db
Normal A-scan (Fig. 12a)	18 db

No comparative data appears to be available for shorter pulses or narrower bandwidths, in which case the effect of fluctuation and therefore of integration would be expected to be greater.

It is of interest to note that other studies for the same pulse length in the same band in which the integration time was varied from 0.05 to 0.5 second showed no systematic variation with integrating time, although this would be expected from theory(49). It is possible that if some integration is performed electronically, the eye itself is capable of further smoothing of the background. On the other hand, the dependence of recognition differential on bandwidth suggests that fluctuation of the background may not be important when the bandwidth is greater than about 200 cps. as it was in this instance.

Various other modifications to the A-scan presentation have been investigated at NRL in relation to possible improvements in recognition differential(44,47,49,50). Use of more than one dimension of the cathode-ray tube to present signal amplitude information (see Figs. 12d, e, h, & i) resulted in no improvement in recognition differential. This result suggests that duplication of information to the observer is of no avail. It remains to be seen if recognition differentials could be improved by use of an additional dimension to present fresh information, such as frequency.

Reference has already been made to the gains associated with integration. Various other signal processing techniques have been investigated at NRL in relation to the A-scan and other presentations(47,51). No marked improvements were found, and it appears that integration is the only process that has a marked effect on recognition differential. However, decreases of 4 db in recognition differential were found(47) when exponential amplifiers with exponents less than unity (namely 0.06) were used, provided the pulse length was 50 milliseconds or less.

Effect of Pulse Length—Available data on the effect of pulse length on recognition differential (41,47) is summarized in Fig. 13(a). As might be expected, the recognition differential increases with decreasing pulse length. For pulse lengths shorter than about 200 milliseconds, the recognition differential rises about 3 db for each halving of the pulse length. This result is in agreement with radar studies where detectability was found to vary directly with pulse length(45, p 109). For pulse lengths longer than 200 milliseconds, the recognition differential changes less rapidly. It is not clear whether this result is a function of the pulse length itself in relation to the observer's ability to average out fluctuations in background level, or a result of the angular size of the pulse as presented to the eye. It will be noted that the NEL recognition differentials are lower than those determined by NRL. This difference has been attributed to differences in the test procedures and presentations(41). It should be noted that the NEL studies were on an integrated scan, found to be the best at NRL.

Effect of Bandwidth—If noise level alone determined the recognition differential, we should expect the recognition differential to increase by 3 db for each doubling of the input bandwidth. But, as the bandwidth is increased, the fluctuation in noise level becomes less, and theoretical considerations suggest that the 3-db dependence is reduced to 1.5 db for each doubling of the bandwidth. The data presented in Fig. 13(a) has been replotted in Fig. 13(b) to illustrate the effect of input bandwidth on the detection of pulses. Some additional data(50) for narrow bandwidths has been added. This data confirms that the recognition differential increases by about 1.5 db for each doubling of the bandwidth, except for large bandwidths, where the rate of increase appears to be greater. It is possible that for large bandwidths, where fluctuation is least, the fluctuation becomes insignificant in detection, and the noise level alone determines the recognition differential.

The energy in a pulse is spread over a band of frequencies which increases as the pulse length is decreased. As the filter bandwidth is reduced, a point is reached where the filter

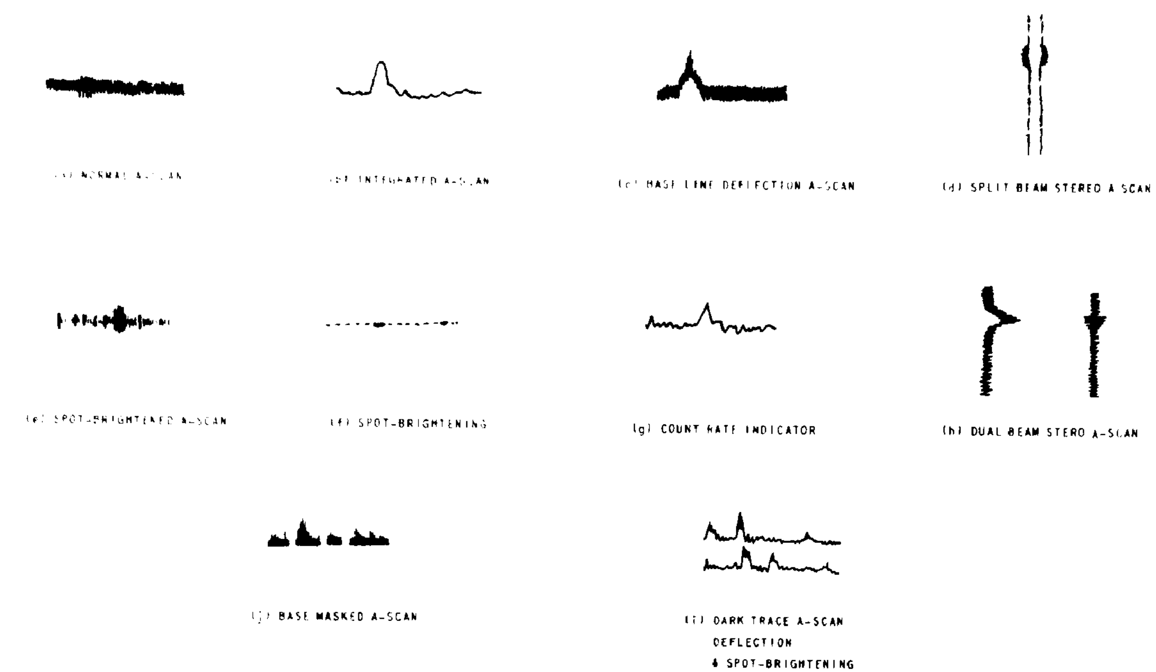
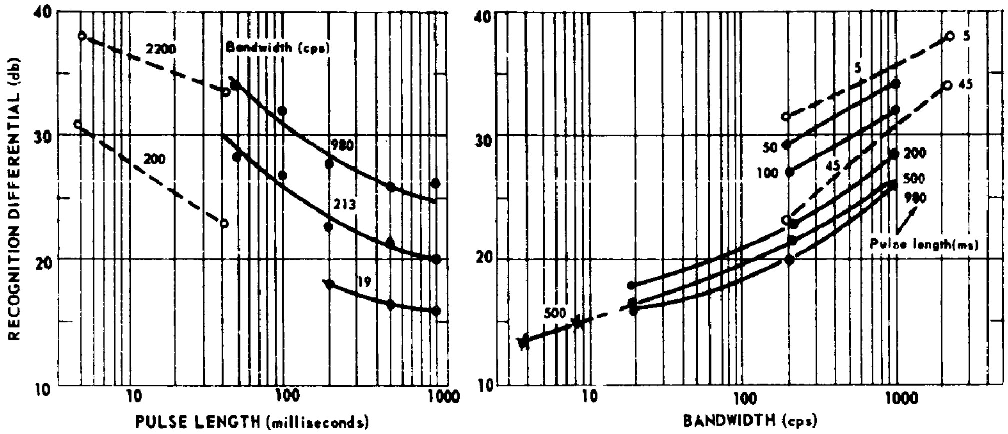


Figure 12 - Some modified A-scans and other scans studied at NRL. (See Dennis, Ref. 44; Hiller & Green, Ref. 47; Matthes & Bradford, Ref. 48 & 49; and Medrow, Ref. 50.)



(a) EFFECT OF PULSE LENGTH

(b) EFFECT OF BANDWIDTH

O — — —O Logarithmic amplifier, rectified envelope, time constant about 1/10 pulse length, NEL data from Schafer & Shewmaker, Ref. 41

●———● No nonlinear circuits, NRL data from Hiller & Green, Ref. 47

x———x A-scan and other presentations, NRL data from Medrow, Ref. 50

Figure 13 - A-scan recognition differentials for pulses in noise

limits the signal energy transmitted. It follows therefore that for a given pulse length an optimum filter bandwidth exists. Radar studies indicate that this occurs when the pulse length-bandwidth product is about unity; values of 1 to 3 have been reported(43).

Repeated Presentation of Pulses—It has been found both at NEL(41) and at NRL(48,49) that repeated A-scan presentation, involving different samples of noise from presentation to presentation, results in a decrease in recognition differential. In the NEL studies, where up to 10 presentations were made, the decrease in recognition differential was about 1.5 db for each doubling of the number of presentations(41). At NRL, where the maximum was 5 presentations and the probability of detection investigated was about 90%(48), the average decrease in signal-to-noise ratio for three integration times was about 2 db for each doubling of the number of presentations(49).

Such gains, which may in part be due to the observer's memory permitting correlation, are probably associated with the background fluctuation, for the greater the number of presentations the greater the chance of the background fluctuations being favorable to signal detection in one presentation. This is demonstrated by the computed transition curves of Fig. 2. In any event, it is unlikely that these gains would be obtained for more than a few presentations. There is some indication however from the NRL studies(49) that when memory is built into the system by the use of a recorded presentation, the gain is somewhat higher. If the data for the three integrating times used in the NRL studies is averaged, the decrease in signal-to-noise ratio for detection for an electronic range recorder is about 2.5 db for each doubling of the number of presentations.

In general, the NRL data on gains from repeated presentations appear unduly high. For recorded presentations a decrease of 1.5 db in recognition differential for each doubling of the presentation appears most probable and is generally accepted. The higher NRL values may be due to the detection criterion used in these tests, which was about 90%(50). The computed transition curves for a number of independent presentations suggest that the curves steepen as the number of presentations increases, and there is some experimental evidence supporting this in the case of a recorded presentation(15). Greater changes in signal-to-noise ratio would be expected therefore if the detection criterion is higher than 50%.

A-Scan Detection of Continuous Modulated Signals—The A-scan is primarily a device for presentation of echo-ranging information, and little attention has been given to its use in passive detection. One study has been reported, however, in which an integrated A-scan was used to detect a modulated wideband noise signal, namely propeller noise(31). The results of this study, which compared the A-scan with other presentations are summarized below:

Presentation	Recognition Differential (db)
Integrated A-scan (time constant, 0.05 sec)	-6
As above with diffraction grating changing the deflection to a color change	-5.5
Magic Eye (time constant, 0.5 sec)	-5
Aural	-9

Signal modulation rate: 2.5 per sec.

These results suggest that the A-scan is inferior to the ear. It is probable, however, that a lower recognition differential would have been obtained if the time constant had been longer and had approached the reciprocal of the modulation rate. In a practical system, however, a range of modulation rates must be accommodated and the time constant can be optimum for only one rate.

The result with the diffraction grating presentation is of interest in that this appears to be the only reported recognition differential for a system employing color as the carrier of signal information. Apparently color is about as good as deflection for this purpose, but a single result of this type cannot be considered as conclusive evidence.

PPI Presentation

There is an extensive literature on threshold signals required for detection using the PPI (42,46), but nearly all of it represents work done in connection with radar.

There are a large number of variables peculiar to the PPI upon which the detection of a PPI pip depends. Some of these are type of screen, scope intensity, focus, ambient light, and sweep rate. The recognition differential for PPI may even be said to depend on range, for the radial distance of the pip as it appears on the screen affects its detectability through the resulting change in pip size and brightness. Some of these variables have been investigated in a quantitative way(45) and there is a much larger descriptive literature, all pertaining to radar. It does not seem practical to attempt to summarize this radar literature. In any event, its applicability to sonar and underwater sound is somewhat dubious because of the great difference in azimuthal sweep rate employed in normal radar and sonar practice. In radar, the sweep rate is commonly so slow that the eye can follow the radial trace in azimuth; in sonar

equipments such as the QHB scanning sonar, the sweep speed is so fast that the eye is not guided in azimuth.

There is one wartime report of a study of PPI recognition differential in connection with sonar(10). It was found that the signal-to-noise ratio (for pulses of the system which approximated QHB) was 2 db, presumably in terms of the total noise level admitted to the system. This value has been used at NEL for prediction purposes(9). It was also found in these wartime tests that the recognition differential was a minimum when the noise background was about 2 db higher than the point of threshold of seeing the noise on the PPI screen. More recent QHBa figure-of-merit tests(2) have confirmed that there is an optimum gain setting for detection.

It is understood that studies of systems involving PPI presentations are now underway at NEL(1). Preliminary signal-to-noise ratios for detection in five pings are as follows:

QHBa (2.7-kc passband) 6 db

SQS.1 (1.6-kc passband) 11 db

where the background level is that measured in the passband of the equipment.* A comparison of various cathode-ray tubes, including the dark-trace tube and the Graphecon, is also being undertaken at NEL but no detailed results are as yet available.

It should be emphasized that a PPI presentation probably requires greater concentration and attention on the part of the observer than other visual presentations. He must continually keep his eyes moving over the screen hunting for a target "pip," and in sonar he is not usually assisted as in radar by being able to follow the sweep line. Radar studies have indicated that if an observer's attention is directed to one part of the screen, he may not observe signals 6 to 8 db above threshold on another position of the screen, and the losses can be as great as 16 db(42). Further, figure-of-merit tests of QHBa equipment have shown that if an observer is alerted as to target bearing, the recognition differential is some 8 db lower than if he is using standard search procedures(2).

Recorded Presentations

Despite the extensive use of the chemical range recorder in operational echo-ranging equipment and the growing importance of recorded presentations in passive detection systems, very little quantitative information on the recognition differential of such devices appears to be available.

Although paper recorders are usually employed, some attention has been given to the use of cathode-ray tubes which will retain information on the phosphor screen(47,49). Certain advantages are claimed for the dark-trace cathode-ray tube as compared with paper recorders; the paper is eliminated and the definition is better than that of the standard chemical paper-type recorder(47). Photographs of the tube face must be taken, however, in order to obtain a permanent record. In general, recorded presentations employ spot brightening. But by using a cathode-ray tube it should be possible to combine the advantages of A-scan presentation and memory in a single display(47,49).

Single-Pulse Detection—Only one systematic study appears to have been reported of the recognition differentials obtainable for pulse detection with the chemical recorder(41). This study was confined to determinations of the recognition differential of pulses in noise for two pulse lengths and two input-bandwidths, Fig. 14. One other value(51) has been added. In addition

*Corresponding recognition differentials for one ping are: QHBa, 43 db, SQS.1, 46 db.

to the normal Sangamo 55100 range recorder paper speed, a slower speed (1/4 normal) was used in the NEL tests(41). No effect on recognition differential for a single ping or for up to 10 pings was observed. It should be noted that the effect on recognition differential of increasing the bandwidth from 200 to 2200 cps is relatively small.

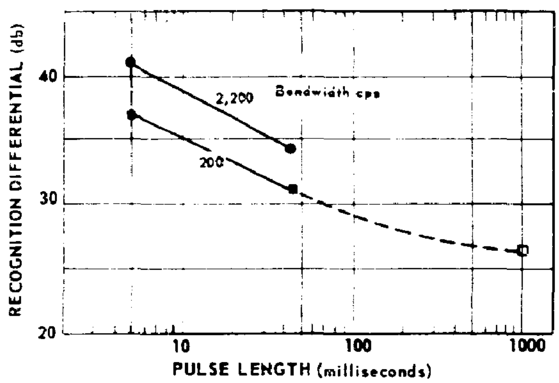


Figure 14 - Chemical recorder recognition differentials for pulses (one sweep)

Comparison of the chemical recorder data, Fig. 14, with that for the A-scan, Fig. 13, indicate that the chemical recorder is somewhat inferior to the A-scan. However, the following comparison of an A-scan and a dark-trace cathode-ray-tube display using spot brightening (the NRL Electronic Range Recorder) for detection of a 500-millisecond pulse in noise (input bandwidth 213 cps)(49) suggests that when both have the benefit of integration, the difference between A-scan and spot brightening may be small.

Integrating Time (sec)	S/N Ratio (db) (90% detection)	
	A-Scan	ERR
0.05	16.5	19
0.25	16	17
0.5	18	17

Passive Detection—The two types of recorded presentation which have been applied to passive detection are spectrum analyzers and bearing indicators. Both employ intensity modulation, the signal level being indicated by intensity of the trace. In spectrum analyzers—for example, LOFAR—signal level is presented as a function of frequency across the paper, the movement of the paper providing the time coordinate. Such devices are particularly suited to the detection of line components.

Recognition differentials for the LOFAR equipment do not appear to be available. Recognition differential data is available, however, for the STROBAR correlator developed at MPL (26), which has a similar presentation. Each channel in this device consists of a chopper, which is equivalent to multiplication by a square-wave signal of fundamental frequency equal to the chopping rate, followed by a low-pass filter and rectifier averager. A range of chopping speeds, one for each channel, are accommodated simultaneously by suitable arrangement of contacts on rotating discs. The outputs of 75 one-cycle channels are presented on a chemical recorder. It has been found that single-frequency signals 3 db lower than the spectrum level of the noise background can just be detected using a single on-off observation in a single channel of this device(26). In the complete STROBAR, the maximum signal required was 3 db higher than the noise-spectrum level, the difference from the single-channel case probably being due to nonuniformity in the channels. Theory indicated a detection threshold of 0 db in terms of the spectrum level of the noise background for the integrating time of 5 seconds employed(26).

In contrast to spectrum analyzers, bearing indicators, which have been utilized at USL on various listening arrays, are applicable to the detection of wideband signals, which may have spectra similar to that of the background. Detection is on a basis of signal and background level alone, which is presented on the recorder as a function of bearing.

Three basic signal processing systems, shown in the table below, have been studied at USL in relation to the detection of wideband signals. It was found that the recognition differentials of the three systems were only slightly different for "incoherent" processing, in which each input consists of signal and masking noise. However, lower detection thresholds may be obtained from a dual-channel processing system with "coherent" inputs when one input consists of a locally generated signal(52).

System	Recognition Differential (db) (Incoherent Inputs, Two Sweeps)
Dual-channel USL clipper correlator type	-14
Dual-channel heterodyne	-12
Single-channel AVC	-12

Input Bandwidth: 1.5 octaves
Averaging Time: optimum for 1-cps modulation

Effect of Number of Presentations—The great advantage of a recorded display is that memory is automatically provided, and the observer has an opportunity to correlate information presented in a whole series of sweeps. Whether used with echo-ranging(41) or passive detection equipment(52,53) it appears well confirmed that the recognition differential of such displays decreases at a rate of 1.5 db for each doubling of the number of sweeps.* This result is to be expected if we consider the observer as an averaging device. Since the averaging time is proportional to the number of sweeps, theory shows that the recognition differential should decrease by 1.5 db for each doubling of the averaging or integrating time.

It would be expected that paper speed and the length of a presentation would set an upper limit to the gains achieved by recording, since the observer must be able to average over the whole presentation to achieve the maximum gain. It is well known, for example, that smaller signals can be detected if the observer looks along the length of a long record than if he looks perpendicular to the record. The limits do not appear to have been determined. It has been reported, however, that improvements in pulse detection of 10 to 20 db relative to a single sweep are readily obtained by repeated presentation(21).

It has been noted above that gains of 1.5 db for each doubling of the number of presentations have also been observed at NEL for a nonrecorded, visual display and for the ear with simulated echoes(41). It is probable, however, that much greater concentration is then required of the operator, and that in any event the gains will not persist for as many presentations. The results of an NRL study(49) on the detection of simulated echoes confirm that the gain from repeated presentation may not be as great for nonrecorded as for recorded displays. The gains observed in this instance, which have been discussed earlier, were higher than the expected 1.5 db, and may be accounted for by the higher probability of detection used as the detection criterion.

Detection of Pulses in Reverberation

A conventional visual presentation provides no frequency discrimination against the background as is the case with aural detection, where the critical bands of the ear limit the masking

*[illegible] refers to sweeps yielding fresh information from sweep to sweep. For example, the background [illegible] from sweep to sweep, or presented at a different time in [illegible] exact replica of the first.

background to a small band of frequencies about the signal frequency. This frequency discrimination on the part of the ear is, as we have seen, particularly important when the background in which an echo has to be detected is reverberation, since it results in low recognition differentials when the echo has appreciable doppler. In this case, visual detection is at a great disadvantage as compared with aural detection, since the input bandwidth of an echo-ranging system must be wide enough to accommodate target doppler. Possibly for this reason very little attention has been given to the determination of visual recognition differentials for reverberation backgrounds, and no values appear to have been reported.

Various attempts have been made to incorporate frequency discrimination in echo-ranging systems using visual presentations which would be expected to improve the detection of echoes in reverberation, but recognition differentials do not appear to be available. For example, multiple narrow-band filters are used in the NRL Sonar Frequency Scanning System, 29 individual filters of 10-cps bandwidth being used to cover a total band of 290 cps(54). The display in this system is a long-persistence cathode-ray tube, the abscissa being frequency (doppler), the ordinate, range, and level being indicated by spot brightness. In field tests of this system positive contact was obtained in 69% of cases when aural detection gave 31%, which indicates from the transition curve (Fig. 2) that the recognition differential was 2 to 3 db lower than for the ear. In these tests the pinglength varied from 0.1 to 1 second and the doppler shift was up to ±70 cps.

COMBINED DISPLAYS

Limited studies have been made of the recognition differential of various combined displays, that is, displays where information on signal and background is presented simultaneously on two devices.

NEL(41) has studied aural A-scan and aural range-recorder presentations in relation to echo detection. A combination of an A-scan and an electronic range recorder has been studied at NRL in connection with the same problem(48,49). Also, various visual presentations in combination with aural detection have been investigated in relation to the detection of modulated wideband signals(38).

In all cases it has been found that, at best, the recognition differential of the combined display is the same as that of the better individual display. Often the combined display is inferior. This may be because of the inability of an observer to divide his attention effectively between the displays(49). Or the observer may detect signals on the better individual display and then reject them because they do not appear on the inferior display. Although the probability of false signals may be lowered in this way, the recognition differential will be impaired.

Duplication of displays may still be desirable, however, for detection. For example, although a recorded presentation may be inferior to the ear or an A-scan for a single presentation, it may be profitable to take advantage of the memory features of the recorder.

It is possible that some improvement might result from the use of combined displays if the additional displays are used to present new information on signal and background, such as [illegible] information in addition to level information, but this does not appear to have been [illegible]. In any event, such gains may be offset by the observer's capabilities of monitoring more than one display. Whatever the nature of the second display, the observer should be [illegible] presentation for confirmation of signals detected on the other [illegible].

[illegible] regarding combined displays appear to be true for target classification. [illegible] classification ability of various combinations of aural, range-recorder, [illegible] with the performance of these devices individually shows that the

combinations are no better for classification of a contact as submarine or nonsubmarine than the best individual device(55).

AUTOMATIC ALARMS

Various schemes for automatic alarms have been proposed in the past; during World War II such devices were considered for the protection against torpedoes of merchantmen and other ships not carrying trained sonar operators. The advantage of automatic alarm is that the presence of a signal can be indicated in a clear, unmistakable manner—such as the ringing of a bell—that requires no interpretation on the part of an observer. Although the recognition differential for such a device may be inferior to that obtained with an optimum observer, it has the advantage of consistent performance with no deterioration due to fatigue.

Some measurements of the recognition differential of such a device have been reported recently(60). The values of recognition differential given in the following table refer to a device in which the integrated levels within two successive range gates are compared. In this device, the signal had to be detected in two successive sweeps before an alarm was given. The recognition differential was considered to be the signal-to-noise ratio at which an alarm was given in 50% of a number of trials. For the reported values, a 5% probability of false indication was allowed.

Automatic Alarm - Recognition Differentials
(Input Bandwidth: 280 cps)

Gate Length (msec)	Recognition Differential (db)	
	105-msec Pulse length	250-msec Pulse length
250	21	--
500	24	19

Surprisingly enough, these values are about the same as those obtained with the ear for signals in wideband noise (Fig. 9) allowing 1.5-db improvement in the case of the ear for two observations.

* * *

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58. [illegible] M. Young and R. R. [illegible], "Axis-Crossing Interval Meter," MIT Acoustics Laboratory Quarterly Progress Report, July-Sept. 1951, pp. 32-34.

59. J. C. Webster, R. S. Gales, and M. Lichtenstein, "Individual Differences in Noise Masked Thresholds," J. Acoust. Soc. Am., Vol. 22, p. 483, July 1950.

60. J. C. Held, "Automatic Sonar Detection Systems" (Confidential), paper presented at 8th U.S. Navy Underwater Acoustics Symposium, 19-20 Nov. 1953.

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DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5660

IN REPLY REFER TO
5510/1
Ser 93/057
20 Jan 98

From: Chief of Naval Research
To: Commanding Officer, Naval Research Laboratory (1221.1)

Subj: DECLASSIFICATION OF DOCUMENTS

Ref: (a) NRL ltr 5510 Ser 1221.1/S0048 of 25 Feb 97
(b) NRL memo Ser 7103/713 of 29 Jan 97
(c) ONR Report "A Summary of Underwater Radiated Noise Data, March 1966"

Encl: (1) ONR Report "A Summary of Underwater Acoustic Data, Part I" AD-030 750
(2) ONR Report "A Summary of Underwater Acoustic Data, Part II" AD-039 542
(3) ONR Report "A Summary of Underwater Acoustic Data, Part III" AD-039 543
(4) ONR Report "A Summary of Underwater Acoustic Data, Part IV" AD-039 544
(5) ONR Report "A Summary of Underwater Acoustic Data, Part V" AD-105 841
(6) ONR Report "A Summary of Underwater Acoustic Data, Part VII" AD-115 204
(7) ONR Report "A Summary of Underwater Acoustic Data, Part VIII" AD-105 842

1. In response to reference (a), the following information is provided:

Enclosure (1) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (2) was downgraded to UNCLASSIFIED by NRL, 12/3/90;
Enclosure (3) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (4) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (5) was downgraded to UNCLASSIFIED by NRL, 12/3/90;
Enclosure (6) was downgraded to UNCLASSIFIED by CNR, 7/29/74; and
Enclosure (7) was downgraded to UNCLASSIFIED by CNR, 7/29/74.

Enclosures (1) through (7) have been appropriately stamped with declassification information and, based on the recommendation contained in reference (b), Distribution Statement A has been assigned.

AD-396 737

2. To my knowledge, reference (c) has not been previously reviewed for declassification. Based on our discussions in April 1997, I am still holding it for Dr. Hurdle's comments.

3. Questions may be directed to the undersigned on (703) 696-4619.

Completed
18 Apr 2000
B.W.

Peggy Lambert
PEGGY LAMBERT
By direction